Fermi National Accelerator Laboratory

FERMILAB-Pub-95/318-E
E687

Search for the Decay of D^+ and D_s^+ Mesons to Three Charged Kaons

P.L. Frabetti et al.
The E687 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

October 1995

Submitted to *Physics Letters B*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

Search for the Decay of D^+ and D_s^+ Mesons to Three Charged Kaons

The E687 Collaboration

P. L. Frabetti
Dip. di Fisica dell'Università and INFN - Bologna, I-40126 Bologna, Italy

H. W. K. Cheung[a], J. P. Cumalat, C. Dallapiccola[b], J. F. Ginkel, W. E. Johns[c], M. S. Nehring[d]
University of Colorado, Boulder, CO 80309, USA

J. N. Butler, S. Cihangir, I. Gaines, P. H. Garbincius, L. Garren, S. A. Gourlay, D. J. Harding, P. Kasper, A. Kreymer, P. Lebrun, S. Shukla, M. Vittone
Fermilab, Batavia, IL 60510, USA

S. Bianco, F. L. Fabbri, S. Sarwar, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

R. Culbertson[e], R. W. Gardner, R. Greene[f], J. Wiss
University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

G. Alimonti, G. Bellini, M. Boschini, D. Brambilla, B. Caccianiga, L. Cinquini[g], M. Di Corato, M. Giammarchi, P. Inzani, F. Leveraro, S. Malvezzi, D. Menasce, E. Meroni, L. Moroni, D. Pedrini, L. Perasso, F. Prelz, A. Sala, S. Sala, D. Torretta[a]
Dip. di Fisica dell'Università and INFN - Milano, I-20133 Milan, Italy

D. Buchholz, D. Claes[h], B. Gobbi, B. O'Reilly[g]
Northwestern University, Evanston, IL 60208, USA

J. M. Bishop, N. M. Cason, C. J. Kennedy[i], G. N. Kim[j], T. F. Lin, D. L. Puseljic[k], R. C. Ruchti, W. D. Shephard, J. A. Swiatek[l], Z. Y. Wu
University of Notre Dame, Notre Dame, IN 46556, USA

V. Arena, G. Boca, C. Castoldi, G. Gianini, S. P. Ratti, C. Riccardi, L. Viola, P. Vitulo
Dip. di Fisica Nucleare e Teorica dell'Università and INFN - Pavia, I-27100 Pavia, Italy.

A. Lopez
University of Puerto Rico at Mayaguez, PR 00709, Puerto Rico

G. P. Grim, V. S. Paolone, P. M. Yager
University of California-Davis, Davis, CA 95616, USA

J. R. Wilson
University of South Carolina, Columbia, SC 29208, USA

P. D. Sheldon
Vanderbilt University, Nashville, TN 37235, USA

F. Davenport
University of North Carolina-Asheville, Asheville, NC 28804, USA

G.R. Blackett, K. Danyo, M. Pisharody, T. Handler
University of Tennessee, Knoxville, TN 37996, USA

B. G. Cheon, J. S. Kang, K. Y. Kim
Korea University, Seoul 136-701, Korea

Abstract

We report the results of a search for the doubly Cabibbo suppressed decays $D^+ \to K^+K^-K^+$ and $D^+ \to \phi K^+$, and the singly Cabibbo suppressed decays $D_s^+ \to K^+K^-K^+$ and $D_s^+ \to \phi K^+$. Our measurements are all consistent with zero branching ratio, and we set 90% confidence level upper limits on the relative D^+ branching ratios: $BR(\phi K^+)/BR(\phi\pi^+) < 0.021$, $BR(K^+K^-K^+)/BR(\phi\pi^+) < 0.025$ and $BR(K^+K^-K^+)/BR(K^-\pi^+\pi^+) < 0.0016$, and the relative D_s^+ branching ratios: $BR(\phi K^+)/BR(\phi\pi^+) < 0.013$ and $BR(K^+K^-K^+)/BR(\phi\pi^+) < 0.016$. The data were accumulated by the Fermilab high energy photoproduction experiment E687.

We report on a search for the decays of D^+ and D_s^+ mesons to the final state $K^+K^-K^+$, including resonant decays via ϕK^+. CP conjugates are implied throughout this letter. These are doubly Cabibbo suppressed decays ($\Delta c = -\Delta s$) for D^+ mesons, and singly suppressed decays for D_s^+ mesons. The branching ratios of doubly Cabibbo suppressed decays are of interest because they provide tests of models of charm decay and because for neutral D mesons they are a potential background to searches for D^0–$\overline{D^0}$ mixing. The WA82 collaboration has reported [1] the observation of $D^+ \to K^+K^-K^+$ with a relative branching ratio of $B(K^+K^-K^+)/B(K^-\pi^+\pi^+) = 5.7 \pm 2.0 \pm 0.7\%$, and the E691 collaboration has published [2] an observation of $D^+ \to \phi K^+$ with a relative branching ratio of $B(\phi K^+)/B(\phi\pi^+) = 5.8^{+3.2}_{-2.6} \pm 0.7\%$. In this letter we report a limit on $B(K^+K^-K^+)/B(K^-\pi^+\pi^+)$ which is in clear disagreement with the WA82 result. Our limit on $B(\phi K^+)/B(\phi\pi^+)$ is below the E691 result but is not statistically inconsistent with it.

The data for this analysis were collected in the 1990–91 run of the Fermilab photoproduction experiment E687. A photon beam (mean energy $\sim$ 220 GeV for triggered events) interacts in a beryllium target. Immediately downstream of the production target is a high resolution microvertex detector consisting of 12 planes of silicon microstrips arranged in three views. Further downstream are two analysing magnets of opposite polarity, and five stations of multiwire proportional chambers (MWPC's). There are three MWPC stations between the two magnets and two stations downstream of the second magnet. Three gas Čerenkov counters provide particle identification. A detailed description of the E687 detector has been published elsewhere [3].

We have searched for the decays $D^+ \to K^+K^-K^+$, $D^+ \to \phi K^+$, $D_s^+ \to K^+K^-K^+$ and $D_s^+ \to \phi K^+$. For simplicity we will refer to the decays $D^+ \to K^+K^-K^+$ and $D_s^+ \to K^+K^-K^+$, which potentially have resonant and non-resonant contributions, as "inclusive" modes. We search for the resonant modes via the decay of the ϕ to K^+K^-. To minimize systematic uncertainties, we determine relative branching ratios:

$$R = \frac{B(D \to KKK)}{B(D \to \text{Norm})} = \frac{N_{\text{obs}}(KKK)}{\epsilon(KKK)}\frac{\epsilon(\text{Norm})}{N_{\text{obs}}(\text{Norm})} = \frac{N_{\text{obs}}(KKK)}{S} \tag{1}$$

where ϵ is the acceptance times efficiency for each mode, S is the experimental sensitivity, and N_{obs} is the number of observed decays (or the upper limit on that number). For normalizing modes, we use the decays $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$. To the extent possible, we apply the same cuts to the normalizing and $K^+K^-K^+$ modes. For the purpose of comparison with experiment WA82, we also determine a branching ratio for the inclusive D^+ mode relative to $D^+ \to K^-\pi^+\pi^+$.

Selection of candidates for D^+ and D_s^+ decays with three charged kaons in the final state begins by subjecting combinations of three charged tracks (total charge = +1) to Čerenkov and vertexing cuts. Tracks are defined as candidate kaons if they are consistent with a Čerenkov hypothesis of kaon or kaon/proton ambiguous. If the track momentum is greater than 60 GeV/c, the Čerenkov system cannot discriminate between pions and kaons. If such tracks are kaon/pion ambiguous, they are also accepted as kaon candidates. In the normalizing modes, no Čerenkov requirements are made on the pion candidates. The three tracks are fit to a common vertex (which we will call the secondary vertex), and the confidence level of this fit must exceed 1%. A candidate-driven vertexing algorithm [3] is used to identify the primary vertex, and this vertex is required to be in the beryllium target.

For the resonant modes $D^+ \to \phi K^+$ and $D_s^+ \to \phi K^+$, we require the K^+K^- mass to be between 1013.9 MeV/c^2 and 1024.9 MeV/c^2. There are two possible K^+K^- combinations; if either passes the ϕ mass cut the event is selected. We also cut on θ^*, the angle between the "bachelor" kaon and the daughter K^+ from the ϕ decay, as seen in the ϕ rest frame. We require $|\cos\theta^*| > 0.5$. For the decay of a pseudoscalar particle to a vector and a pseudoscalar, $dN/d\cos\theta^*$ is distributed as $\cos^2\theta^*$, while for background this distribution is typically flat.

At this point we tighten the Čerenkov requirements on kaons that do not come from ϕ candidates. For ϕK^+ modes, the bachelor kaon is required to be kaon definite or kaon/proton ambiguous (tracks with $p > 60$ GeV/c that are kaon/pion ambiguous are no longer accepted). For the inclusive modes, all three kaons must pass this tighter cut.

For the long lived D^+ mesons, we require that the secondary vertex lie outside ("downstream") of the beryllium target. A significant fraction of produced D^+ mesons pass this cut, and backgrounds are reduced by roughly an order of magnitude. The significance of detachment of the secondary and primary vertices, ℓ/σ_ℓ, is defined as the distance (ℓ) between the two vertices divided by the error (σ_ℓ) on ℓ. We require $\ell/\sigma_\ell > 4.0$. Two additional cuts are made for the inclusive D^+ mode. We increase the confidence level cut on the secondary vertex to 10%, and we require that the primary vertex be isolated from the secondary vertex ("primary isolation cut"). Tracks assigned to the secondary vertex are added one at a time to the primary vertex, a fit to the new "primary" is performed, and the candidate is cut if the confidence level of any fit is greater than 15%. Invariant mass plots for the resulting D^+ resonant and inclusive mode candidates are shown in Fig. 1((a) and (b)). The corresponding plots for the normalizing mode $D^+ \to \phi\pi^+$ are shown in Fig. 2((a) and (b)). In Fig. 2, a sideband subtraction has been performed to remove the non-resonant background. This is done using two sidebands in the K^+K^- mass plot between 991.9 MeV/c^2 and 1002.9 MeV/c^2 and between 1035.9 MeV/c^2 and 1046.9 MeV/c^2. Candidates for the normalizing mode $D^+ \to K^-\pi^+\pi^+$ are shown in Fig. 3.

We do not require that the secondary vertices in D_s^+ decays occur outside of the target, due to the shorter D_s^+ lifetime. To compensate, we increase the cut on the significance of detachment ($\ell/\sigma_\ell > 8.0$) and on the confidence level of the secondary vertex (CL > 10%). For the inclusive D_s^+ mode, we make the same primary isolation cut we make on the inclusive D^+ mode, and we also cut on the isolation of the secondary vertex. Tracks not assigned to either the primary or secondary vertex are added one at a time to the secondary vertex. The D_s^+ candidate is rejected if the confidence level of the fit to any of the resulting vertices is greater than 0.01%. The invariant mass plots for resonant and inclusive D_s^+ mode candidates are shown in Fig. 1((c) and (d)). The corresponding plots for the normalizing mode $D_s^+ \to \phi\pi^+$ are shown in Fig. 2((c) and (d)).

We see no evidence for a signal in any of the four $K^+K^-K^+$ modes (Fig. 1). The Particle Data Group has suggested [5] a method for setting upper limits in the presence of backgrounds. If the estimated background in the signal region is μ_B, and the number of expected signal events in the signal region is N, then the probability of observing n or fewer events is

$$p_n(\mu_B, N) = \frac{e^{-N}\sum\limits_{j=0}^{n}(\mu_B+N)^j/j!}{\sum\limits_{j=0}^{n}(\mu_B)^j/j!} \tag{2}$$

The upper limit on the number of signal events (n^*) is that value of N for which $0.1 = p_{n_0}(\mu_B, N) = p_{n_0}(\mu_B, n^*)$, where n_0 is the total number of events observed in the signal region.

This method does not allow for uncertainties in the experimental sensitivity S and assumes the background in the signal region is known without error [6]. There does not seem to be a generally accepted approach [7] for including contributions from these "systematic errors". We have adopted the following method for incorporating systematic errors into our limit determination.

From Eq. (1), the number of expected signal events is $N = R \cdot S$. Equation (2) then becomes:

$$p_n(\mu_B, R, S) = \frac{e^{-RS} \sum\limits_{j=0}^{n} (\mu_B + RS)^j / j!}{\sum\limits_{j=0}^{n} (\mu_B)^j / j!}$$

If $\hat{S}$ is our measured sensitivity, and σ_S its error, we compute the weighted average:

$$\langle p_n(\mu_B, R) \rangle = \int_0^\infty p_n(\mu_B, R, S) \, \frac{1}{\sqrt{2\pi}\sigma_S} e^{-(\hat{S}-S)^2/2\sigma_S^2} \, dS$$

The 90% confidence level upper limit on the quantity R is that value of R for which $0.1 = \langle p_{n_0}(\mu_B, R) \rangle$. This method assumes that the ratio $\hat{S}/\sigma_S$ is sufficiently large ($>$ 3 or so), and ignores uncertainties in μ_B [8]. Note that Table 1 should provide sufficient information so that alternative methods may be used to incorporate the contributions of systematic errors.

The input parameters used in determining our 90% upper confidence level limits are shown for each mode in Table 1. The signal region of each mass plot is 1.855–1.885 GeV for D^+ modes and 1.955–1.985 GeV for D_s^+ modes; n_0 is the total number of events in this region. The signal regions are a little more than $\pm 3\sigma$ wide: according to MC our experimental mass resolution for these decay modes is 4–5 MeV. The estimate of the background, μ_B, in the signal region is determined from bins between 1.7–2.1 GeV, excluding bins in the signal regions (1.825–1.915, 1.925–2.015 GeV). The number of normalizing events are determined by fitting the mass plots shown in Figs. 2 and 3 with a Gaussian combined with a second order polynomial. The masses found with these fits are in good agreement with world averages [4], and the widths are consistent with our Monte Carlo predicted resolutions. Monte Carlo methods are used to calculate $\epsilon(KKK)/\epsilon(\text{norm})$, and this factor includes the branching ratio for $\phi \to K^+K^-$ [9].

The cuts described above were chosen to maximize our sensitivity to each decay mode. Our sensitivity was estimated using efficiencies from Monte Carlo and background estimates from sidebands in the data. The limits we obtain are stable for reasonable changes in each of the selection cuts.

One advantage of the three kaon final state is that misidentified charm decays typically do not give reflections in the D^+ mass region. This is not true in the D_S^+ mass region, where misidentified $D^+ \to \phi\pi^+$ decays are a potential problem. From Fig. 1((c) and (d)) it can be seen that this background cannot be very large. Our tight Cerenkov cuts on the bachelor kaon should eliminate much of this background: we estimate that the probability a pion will pass these cuts is 1%.

The primary sources of systematic error in this analysis are (a) uncertainty in the Monte Carlo efficiency for kaons, (b) uncertainty in the Monte Carlo charm meson momentum spectrum, and (c) the statistical error on the number of events in the normalizing mode.

We have tested our Monte Carlo prediction of the kaon efficiency and find it is accurate with an uncertainty of 5%. We use this as our systematic error on the relative efficiency (this is increased to 10% when the decay mode $D^+ \to K^-\pi^+\pi^+$ is used as the normalizing mode).

The produced D^+ momentum spectrum generated by the PYTHIA based photon-gluon fusion Monte Carlo [10] differs slightly from one we obtain from data. To study the impact of differing D^+ momentum spectra, we find the momentum dependent efficiencies for $D^+ \to K^+K^-K^+$ and $D^+ \to \phi\pi^+$, using the PYTHIA Monte Carlo. The average efficiency is the convolution of the normalized momentum spectrum and the momentum dependent efficiency. Calculating the average efficiency in this way, we find that the relative efficiency $\epsilon(K^+K^-K^+)/\epsilon(\phi\pi^+)$ changes by 3.0% when we use the spectrum obtained from data instead of the PYTHIA spectrum. We use this as our estimate of the systematic error for this effect.

Finally, there is the statistical error on $N(\text{norm})$, which comes from the fit to the appropriate mass plot. For the D^+ (D_s^+) $\phi\pi^+$ modes, this error is 10% (7%). For the $K^-\pi^+\pi^+$ mode, it is 1.5%.

Combining these three errors in quadrature, we find the total systematic errors given in Table 1. In Table 2, we compare the limits we obtain for each mode to previously published results from WA82 [1] and E691 [2]. Our limit on the inclusive D^+ mode is in clear disagreement with the WA82 result. Our limit on the D^+ relative branching ratio $B(\phi K^+)/B(\phi\pi^+)$ is below the E691 result but is not statistically inconsistent with it.

In summary, we report the results of a search for the doubly Cabibbo suppressed decays $D^+ \to K^+K^-K^+$ and $D^+ \to \phi K^+$, and the singly Cabibbo suppressed decays $D_s^+ \to K^+K^-K^+$ and $D_s^+ \to \phi K^+$. Our measurements are all consistent with zero branching ratio, and we set upper limits on the relative D^+ branching ratios: $BR(\phi K^+)/BR(\phi\pi^+) < 0.021$, $BR(K^+K^-K^+)/BR(\phi\pi^+) < 0.025$ and $BR(K^+K^-K^+)/BR(K^-\pi^+\pi^+) < 0.0016$, and the relative D_s^+ branching ratios: $BR(\phi K^+)/BR(\phi\pi^+) < 0.013$ and $BR(K^+K^-K^+)/BR(\phi\pi^+) < 0.016$.

We wish to acknowledge the assistance of the staffs of the Fermi National Accelerator Laboratory, the INFN of Italy, and the physics departments of the collaborating institutions. This research was supported in part by the National Science Foundation, the U.S. Department of Energy, the Italian Istituto Nazionale di Fisica Nucleare and Ministero dell'Università e della Ricerca Scientifica e Tecnologica, the Korean Science and Engineering Foundation, and the Vanderbilt University Research Council.

REFERENCES

[a] Present address: Fermilab, Batavia, IL 60510, USA.
[b] Present address: University of Maryland, College Park, MD 20742, USA.
[c] Present address: University of South Carolina, Columbia, SC 29208, USA.
[d] Present address: Vanderbilt University, Nashville, TN 37235, USA.
[e] Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA.
[f] Present address: Syracuse University, Syracuse, NY 13244-1130 , USA.
[g] Present address: University of Colorado, Boulder, CO 80309, USA.
[h] Present address: State University of New York at Stony Brook, Stony Brook, NY 11794-3800, USA.
[i] Present address: AT&T Bell Labs, West Long Branch, NJ 07764, USA.
[j] Present address: Pohang Accelerator Laboratory, Pohang, Korea.
[k] Present address: Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA.
[l] Present address: Science Applications International Corporation, McLean, VA 22102, USA.

[1] WA82 Collaboration, M. Adamovich *et al.*, Phys. Lett. B **305**, 177 (1993).
[2] E691 Collaboration, J. C. Anjos *et al.*, Phys. Rev. Lett. **69**, 2892 (1992).
[3] E687 Collaboration, P. L. Frabetti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 519 (1992).
[4] Particle Data Group, L. Montanet *et al*, Phys. Rev. D **50** (1994).
[5] *ibid.*, **50**, 1281 (1994).
[6] It also assumes that n_0 and μ_B are statistically consistent.
[7] see, for example: R. D. Cousins and V. L. Highland, NIM **A320**, 331 (1992), and the references therein.
[8] We were unable to find a reasonable method for incorporating Poisson fluctuations in μ_B. Cousins and Highland discuss this difficulty in their paper (reference [7]).
[9] We use the Particle Data Group (reference [4]) value of $B(\phi \to K^+K^-) = 49.1 \pm 0.9\%$.
[10] T. Sjöstrand, PYTHIA 5.6 and JETSET 7.3: Physics and Manual, CERN-TH.6488/92 (1992).

TABLES

TABLE I. 90% C.L. Upper Limits

D	R	n_0	μ_B	N(norm)	$\frac{\epsilon(KKK)}{\epsilon(\text{norm})}$	$\sigma_S(\%)$	Limit
D^+	$B(\phi K^+)/B(\phi\pi^+)$	1	3.14	149.5	0.907	11.6	< 0.021
	$B(K^+K^-K^+)/B(\phi\pi^+)$	6	9.55	92.7	1.879	11.6	< 0.025
	$B(K^+K^-K^+)/B(K^-\pi^+\pi^+)$	6	9.55	6096.0	0.448	11.0	< 0.0016
D_s^+	$B(\phi K^+)/B(\phi\pi^+)$	5	8.73	376.7	0.801	9.1	< 0.013
	$B(K^+K^-K^+)/B(\phi\pi^+)$	13	19.1	210.0	1.605	9.1	< 0.016

TABLE II. Comparison to previously published results.

D	R $(\times 10^2)$	E687	E691	WA82
D^+	$B(\phi K^+)/B(\phi\pi^+)$	< 2.1	$5.8^{+3.2}_{-2.6} \pm 0.7$	
	$B(K^+K^-K^+)/B(\phi\pi^+)$	< 2.5		$49 \pm 23 \pm 6$
	$B(K^+K^-K^+)/B(K^-\pi^+\pi^+)$	< 0.16		$5.7 \pm 2.0 \pm 0.7$
D_s^+	$B(\phi K^+)/B(\phi\pi^+)$	< 1.3	< 7.1	
	$B(K^+K^-K^+)/B(\phi\pi^+)$	< 1.6		

FIGURES

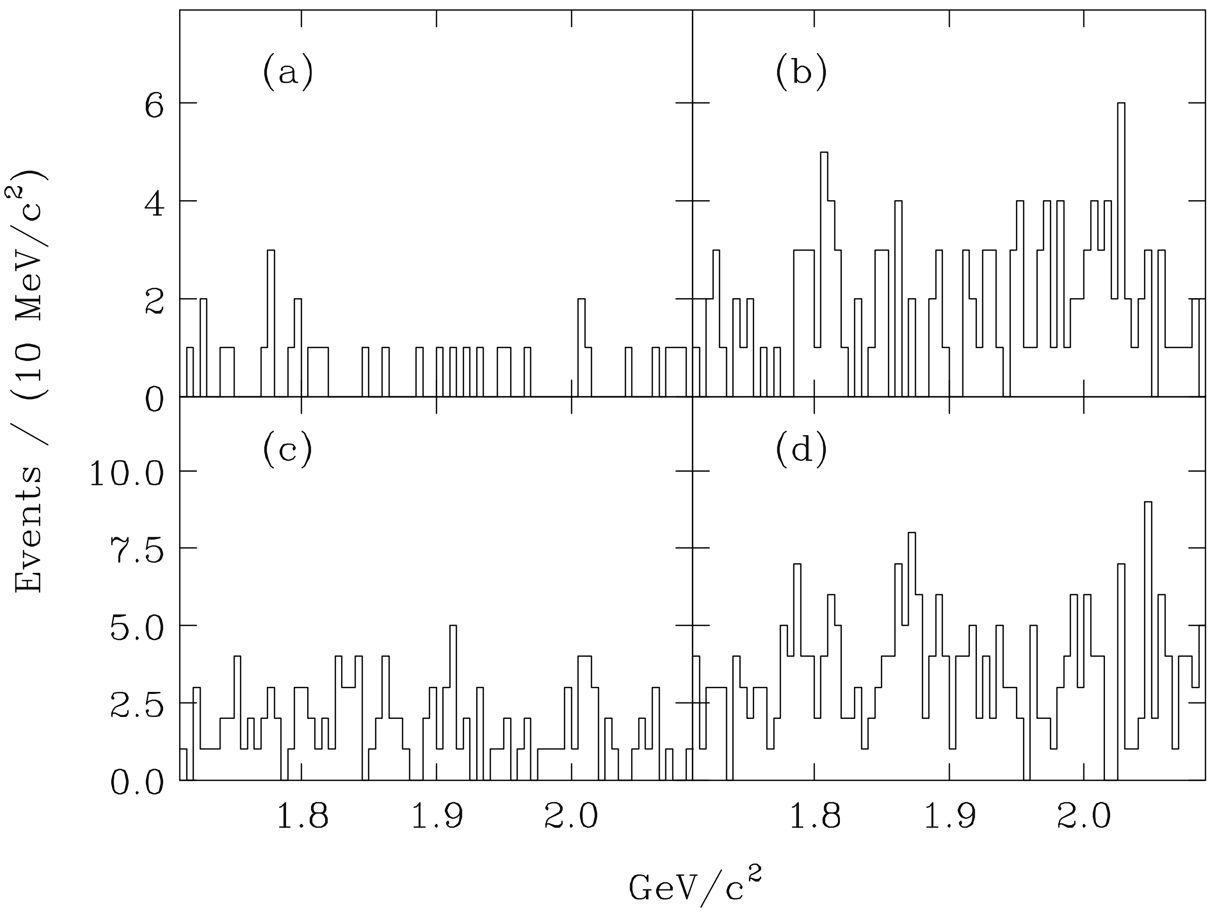

FIG. 1. Invariant mass plots for a) $D^+ \to \phi K^+$ b) $D^+ \to K^+K^-K^+$ c) $D_s^+ \to \phi K^+$and d) $D_s^+ \to K^+K^-K^+$ candidates, after the cuts described for the text.

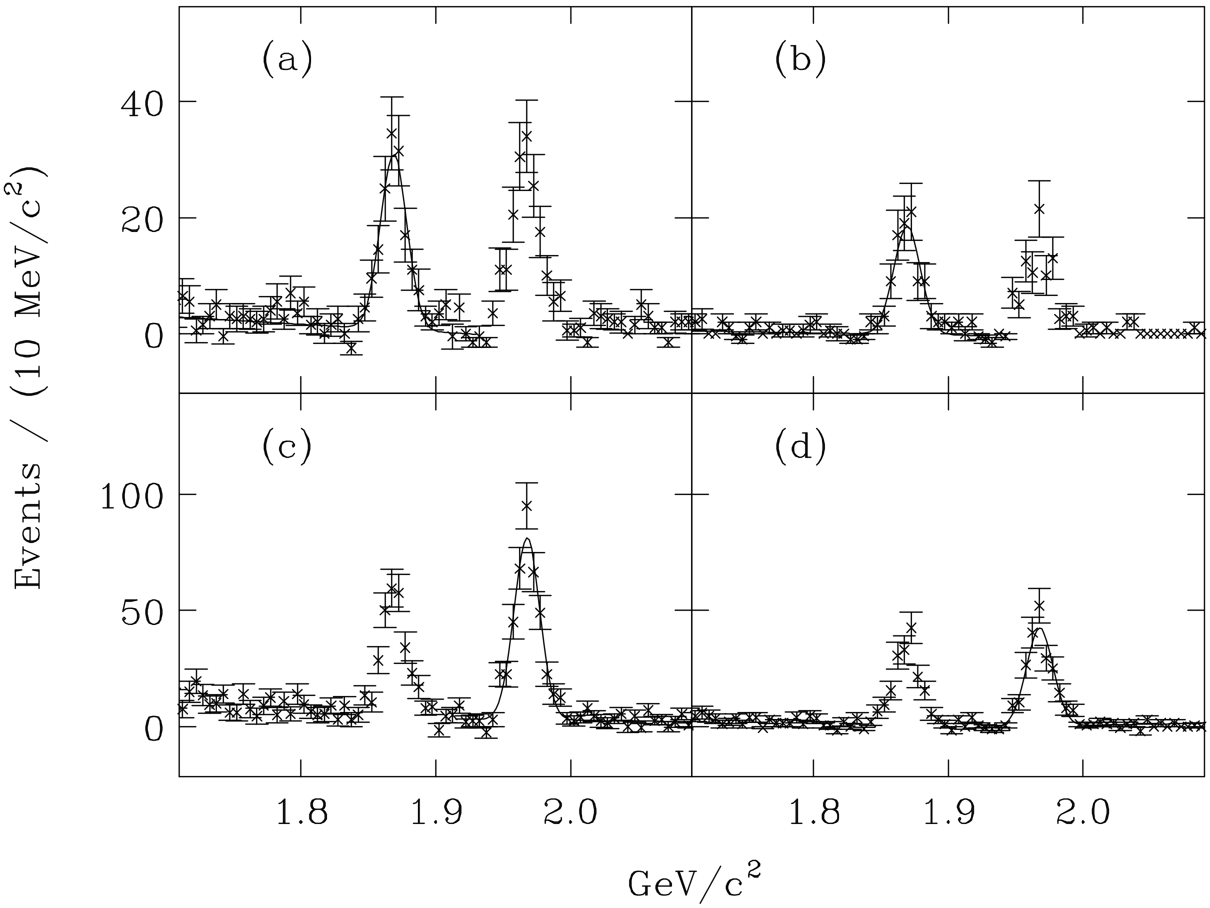

FIG. 2. Invariant mass plots for a) $D^+ \to \phi\pi^+$ b) $D^+ \to \phi\pi^+$ c) $D_s^+ \to \phi\pi^+$ and d) $D_s^+ \to \phi\pi^+$ candidates. The cuts applied to extract each signal correspond to those made in figure 1(a)–(d). A ϕ sideband subtraction has been performed to remove the non-resonant portion of the signal.

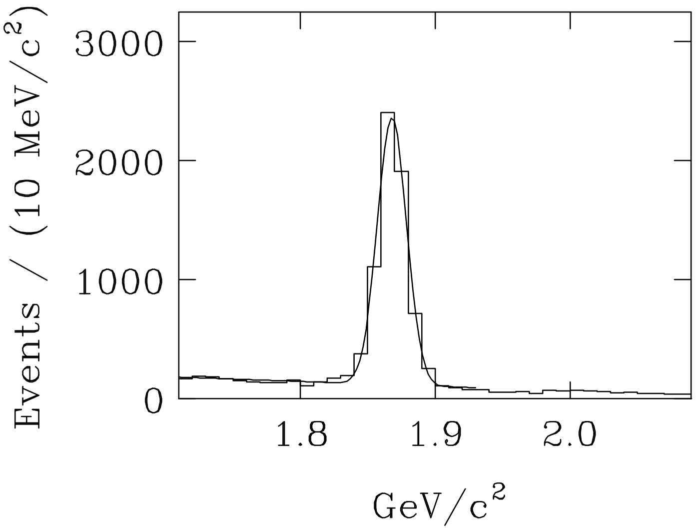

FIG. 3. Invariant mass plot for $D^+ \rightarrow K^-\pi^+\pi^+$, with cuts corresponding to those used to extract the mass plot shown in figure 1(a).